Assessment of Variable Speed Limits from the Drivers' Perspective

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Abstract — **Evaluating of Variable Speed Limits (VSL) is often only possible in indirect ways due to the lack of sufficient data. Since the majority of safety benefits is expected from warning and increased alertness of drivers, evaluation methods that focus on the informative nature of VSL such as the detection rate (DR) and false alarm rate (FAR) are useful tools. In the state-of-the-art these are typically defined from the system's perspective. In this paper, an assessment based on DR and FAR defined from the drivers' perspective is presented, using vehicle trajectories integrated from speed data, hereby evaluating the performance of the VSL by the effectiveness of warning drivers. Appropriate visualization of DR and FAR over traffic speed contours in space and time allows identifying locations or traffic conditions in which missed detections or false alarms are concentrated, so that targeted measures for improvement can be taken. Using the presented method, the VSL system around Antwerp (Belgium) is evaluated. Suggestions for improvement of safety and credibility are highlighted and evaluated using the assessment from the driver perspective.**

I. Introduction

ALTHOUGH travel demand within a day and from day to day is highly variable, the available infrastructure is rather static. To maximize the infrastructure's flexibility in coping with the wide range of possible traffic situations, road authorities are increasingly deploying dynamic traffic management measures such as vehicle-dependent signaling, ramp metering and variable message signs - e.g. variable speed limits (VSL).

Whereas most of these measures seek to optimize the use of available capacity and to increase the system's throughput, the main purpose of VSL is traditionally safety improvement. Some studies also anticipate a positive effect on the efficiency of traffic flow (mainly due to more efficient lane use and fewer lane changes). However, no such positive effect could irrefutably be established in current VSL implementations and field operational tests (e.g. [1]-[3]). Recent research aims at employing VSL to increase the throughput by avoiding capacity drop – i.e. the queue discharge rate is lower than the maximum intensity of free flowing traffic – by suppressing shockwaves ([4], [5]) or by controlling the inflow into daily bottlenecks, keeping it at or just below the free flowing capacity ([6]). The simulation tests in these studies yield promising results, but validation through field operational tests has not been established yet.

Improved safety through VSL on the other hand has been confirmed by several studies. Reduction in accident rates ranging from 15-35% have been reported in the Netherlands, the UK and Germany ([7]-[9]). Because the assessment of safety improvement from accident statistics takes multiple years of data, this is only possible for VSL-systems that have been implemented for a considerable period already - and even then, the comparison is complicated by the influence of various exogenous factors (e.g. increased travel demand).

Evaluating new applications is only possible in indirect ways. Some studies (e.g. [10], [11]) try to relate the safety benefits of VSL to speed variance and the number of short headways. Such surrogate safety measures mainly relate to the safety benefits resulting from smoothening or homogenization of traffic flows at fairly high speeds (avoiding instabilities and dangerous situations). However, the major safety benefits of VSL arise from warning for queue tails (increasing alertness of drivers). This is clear from the fact that the reduction in secondary accidents is significantly higher than the accident reduction overall ([12]). Moreover, safety benefits from homogenization decline with compliance to the VSL; and observations systematically show very poor compliance (in absence of enforcement). Of course, another factor is the applied strategy. If for instance the sole strategy of a VSL system is to warn drivers for queue tails, the safety benefits from homogenization will obviously be rather limited.

Due to the fact that the major safety benefits result from warning, assessment methods that focus on the informative nature of VSL such as the detection rate (DR), false alarm rate (FAR) and the stability (e.g. measured by the amount of VSL displayed very briefly) are useful tools - even though no comparison is possible with the traffic situation before the VSL were operational. On the other hand – in contrast to analyses of accident rates – this means that an assessment can also be made if traffic data prior to the implementation of the VSL is lacking or dated. In [13] is stated that a safety assessment of VSL systems should at least take into account some measure of DR and FAR.

In this paper, the DR and FAR are defined from the drivers' perspective. This way, the DR and FAR represent more correctly (in comparison to existing definitions) the effectiveness of warning drivers for downstream congestion or hazards - regarding both safety benefits and the credibility of a VSL system. A second contribution of this paper is that

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VSL, detections and alarms are visualized (in time and space) in direct comparison with the measured speeds. By doing so, the DR and FAR are no longer global measures for the overall performance of the system, but can be analyzed locally. Locations and traffic situations where the system performs poorly become apparent immediately and ways to improve can be more easily defined.

This paper is structured as follows. Section II generally introduces DR and FAR, which are further defined from the drivers' perspective in Section III. Section IV elaborates on the VSL, detection and alarm visualizations. In Section V, the presented methods are applied in a case study of the VSL system around Antwerp (Belgium). In Section VI, an ex-ante analysis of a modification to the current system (that filters out high frequent fluctuations of the VSL in congested areas) is presented. Conclusions and future research directions are discussed in Section VII.

II. Detection Rate and False Alarm Rate

In the introduction, the usefulness of assessment methods based on DR and FAR was stressed. The DR can be regarded as the most important measure of the two, since it indicates how often drivers are not (appropriately) warned for dangerous situations. The FAR rather relates to the credibility of the VSL system. If the FAR is low, warnings are reliable messages to drivers that encourage them to reduce speed and increase their alertness. A high FAR on the other hand will cause drivers to ignore warnings, thus also (indirectly) decrease safety. Another indicator for the credibility is the stability of the VSL. A high percentage of very short warnings or frequently changing VSL are not reliable messages.

For assessment methods based on DR and FAR, definitions of what constitutes a 'situation that needs to be detected', a 'missed detection' and a 'false alarm' are needed, which can be rather subjective in nature. In the state-of-the-art, these are typically defined from the system's perspective. In [14] for instance, a detection is only considered 'missed' if congestion spillback reaches the first upstream gantry before an appropriate VSL is displayed there.

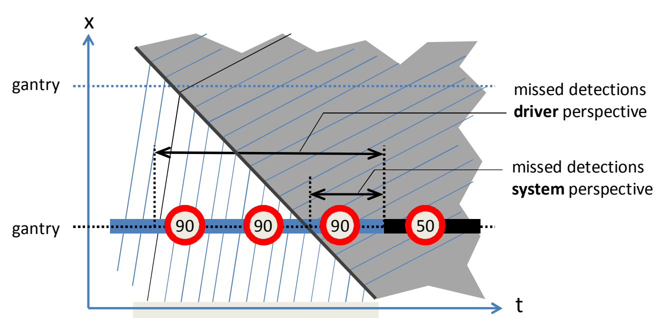

Figure 1: Missed detections from drivers' and system's perspective

When estimating the expected safety benefits from warning drivers and credibility on the basis of DR and FAR, it seems only natural to define these from the drivers' perspective. This way, these measures express most accurately how successful the warning of drivers with VSL is. A detection (missed or not) then coincides with a situation (e.g. a speed drop at a queue tail) that drivers encounter, for which they should have been warned. The difference between system's and drivers' perspective of missed detections is illustrated in Figure 1. A false alarm defined from the drivers' perspective corresponds to a warning shown to drivers that is not followed by a situation that justifies the warning.

III. Assessment from the Drivers' Perspective

This section proposes to assess VSL warning for speed drops due to downstream congestion based on definitions of DR and FAR from the drivers' perspective.

The definition of DR and FAR from the drivers' perspective is based on vehicle trajectories (as illustrated in Figure 1). The required input consists of speed data from detectors and a logging of the displayed VSL. If the VSL can differ between lanes, trajectories should be derived for each lane separately. Otherwise, trajectories representing the entire freeway cross-section (based on speed data harmonically averaged over the lanes) can be chosen. The trajectories should of course correspond to experienced and not instantaneous travel times (as in e.g. [15]). From the trajectories, the time at which a vehicle crosses a gantry and the VSL displayed at that time (if any) are known. To derive DR and FAR from this, the following definitions are needed:

- *Situation to be detected:* the lower bound of the detected speed on a trajectory between two gantries is lower than a chosen threshold. A warning should be displayed at the upstream gantry.
- *Missed detection:* a situation as described above that was not preceded (on the same trajectory) by an *appropriate* VSL at the upstream gantry. Appropriate is defined here as a VSL that is not higher than the lowest detected speed on the downstream trajectory plus a maximal allowable deviation. An exception to this rule is the lowest VSL, which is always considered appropriate (with respect to missed detections, not to false alarms), simply because the system cannot respond in a more appropriate way. If the lowest VSL is an insufficiently safe warning for the worst speed drops (a standstill), the system should be changed to allow lower VSL. A detection that is not missed is a *successful detection*.
- *False alarm:* An alarm is a VSL (lower than the regular speed limit) that is directly invoked by a speed drop detected in the subsequent freeway section (from this to the next gantry). VSL that are (part of) a gradual decrease towards an alarm, leveling over multiple gantries, or other post processing should be disregarded. An alarm that is more than a maximal allowable deviation below the

lower bound of the detected speed (on the same trajectory, until the next gantry) is a *false alarm*.

Based on the above, the DR and FAR are defined as:

- *Detection Rate (DR):* the rate of successful detections over all situations to be detected.
- *False Alarm Rate (FAR):* the rate of false alarms over all alarms

The above definitions include a few parameters. The threshold for the situations to be detected should be chosen such that speeds below the threshold correspond to potentially dangerous situations, whereas higher speeds are (reasonably) safe. Of course, this depends on e.g. the road type and the regular speed limit. A natural choice for this DR threshold is the following. To invoke VSL with the purpose of directly warning for downstream congestion (e.g. VSL of 70 km/h and lower), a VSL control algorithm typically uses thresholds for the detected speeds (e.g. equal to the corresponding VSL). The DR threshold could be chosen equal to the threshold used in the control algorithm to invoke the highest warning VSL (in this example the DR threshold would thus also be 70 km/h). A reasonable value for the allowed deviation between VSL and the lower bound of the detected speed (determining if a detection is missed, or an alarm is false) is the interval between two consecutive VSL (usually 20 km/h). For example, a VSL of 70 km/h followed by a detected speed of 49 km/h would be a missed detection; a VSL of 50 km/h should have been displayed. Analogously, if the lowest detected speed on a section between two gantries is 71 km/h, a VSL of 50 km/h at the upstream gantry is a false alarm. Other values could of course be opted for. For instance if the interest lies in the most dangerous missed detections, a higher deviation could be chosen to select only the largest mismatches between VSL and detected speed. Also, as compliance to the VSL increases, the deviation allowed for false alarms should be decreased. If compliance is strict, obviously no FAR can be measured from detected speeds.

The example in Figure 2 shows the detected speeds on a vehicle trajectory (the full line), with 5 gantries (located at the dashed lines). The driving direction is from left to right (x=0 to 4500m). The horizontal axis has a second interpretation in the time dimension (the time the vehicle passes a location). At the locations of the gantries, the VSL displayed at the time the vehicle passes the gantry is depicted as a colored dot. Mismatches between VSL and detected speeds are either missed detections or false alarms. With an allowed deviation of 20 km/h, the VSL of 50 km/h at the second gantry is a false alarm, and the VSL of 70 km/h at the fourth gantry is a missed detection.

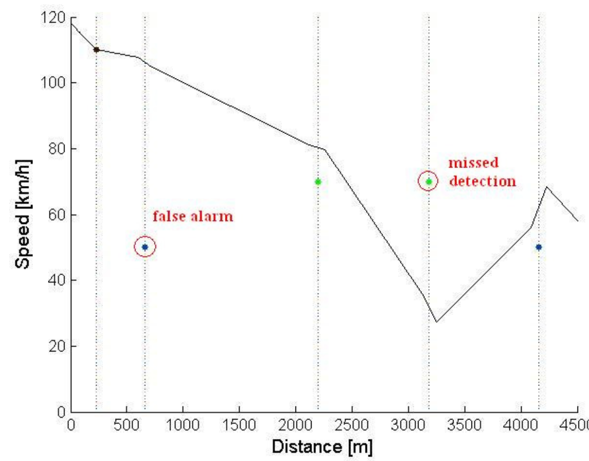

Figure 2: Detected speed on a trajectory and the VSL

By evaluating a large number of vehicle trajectories and adding up (missed) detections and (false) alarms, the resulting DR and FAR reflect how drivers perceive the VSL. This way, the performance of the VSL is assessed by the effectiveness of warning drivers. Hereby, a high DR (direct safety benefits) and a low FAR (indirect benefits because of a higher credibility) are desired. Typically, the DR and FAR are inversely correlated. When fine-tuning a VSL-system, an improvement of one measure has to be weighed against a deterioration of the other. Defining an objective valuation of DR against FAR would require extensive research into their exact impact on safety. In this paper, we limit ourselves to stating that, in general, priority should go out to the DR, since this brings about direct safety benefits.

Finally, note that the presented method is also applicable for warning strategies for weather conditions (e.g. fog). However, since the character of such hazards is more global and static, a simpler method (not based on vehicle trajectories) probably suffices.

IV. VSL, Detection and Alarm Visualization

In this paper, a comprehensible way to look at the local performance (at gantries or for specific periods of the day) is introduced, namely depicting detections, alarms and VSL in comparison to the measured traffic conditions. These visualizations (in time-space diagrams) of traffic states and system reaction and performance in one graph form a very helpful addition, in the sense that they lift the drawback that the DR and FAR are only global measures for the overall performance of the system. Local mismatches between detected speeds and the reaction of the VSL system can easily be identified, and locations and traffic situations where the system performs poorly immediately become apparent. The local visualizations thus strongly aid in defining ways to improve the performance.

Moreover, perspective is added to the global analysis. For example, not all missed detections are equally undesirable. Missed detections at queue tails are generally most dangerous, since these involve large speed differences between approaching traffic and the downstream queue.

Missed detections in the congested centre of a jam are less dangerous, and the major harm there lies in the fact that the credibility of the system is undermined. Moreover, at the head of the queue it might even be desirable to allow more missed detections, in favor of encouraging drivers to accelerate efficiently from the queue by displaying higher VSL.
Examples of visualizations of local VSL reaction and performance are preserved for the next sections, where the case study of the Antwerp VSL system is presented (see Figure 3-Figure 6 and Figure 8-Figure 11.

V. CASE STUDY

The assessment method presented in Section III and IV was developed for use in the evaluation of the VSL system on the highway network around Antwerp (Belgium). The network more precisely comprises the beltway around Antwerp and part of a radial highway towards this beltway (E313 motorway). The VSL system applies a control algorithm that uses speed and density measurements from camera detectors. The primary function is warning drivers for downstream congestion. The regular speed limit in the network is 100 and 120 km/h on the beltway and E313 respectively. The VSL algorithm can impose two reduced speed limits, 50 and 70 km/h, with higher speeds (70, 90 or 100 km/h) displayed on the upstream gantries to guarantee a gradual speed reduction. The VSL are not enforced and from the detected speeds it is clear that compliance is poor.

For this evaluation, one week of traffic data and the logging of the displayed VSL are available.

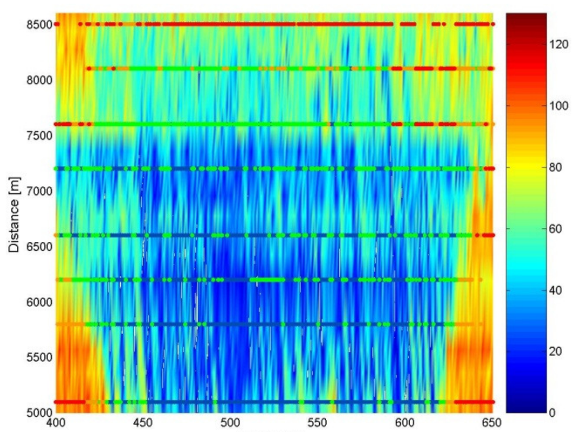

Figure 3: Daily congestion on the beltway and the displayed VSL (right lane; speed in km/h)

Roughly speaking, two different types of daily congestion are noted. On the beltway, large traffic jams with a relatively constant traffic state occur (lasting several hours and covering several kilometers). On the E313, the morning peak period is characterized by a stop-and-go pattern, with fast spillback waves of heavy congestion alternating with high speed (80-100 km/h) acceleration waves. Figure 3 and Figure 4 are examples of these two congestion types. The detected speeds (km/h) are depicted in a space-time diagram. Also, the VSL that were displayed are depicted at each gantry, with the color representing the speed limit (50-70-90-100-120 km/h).

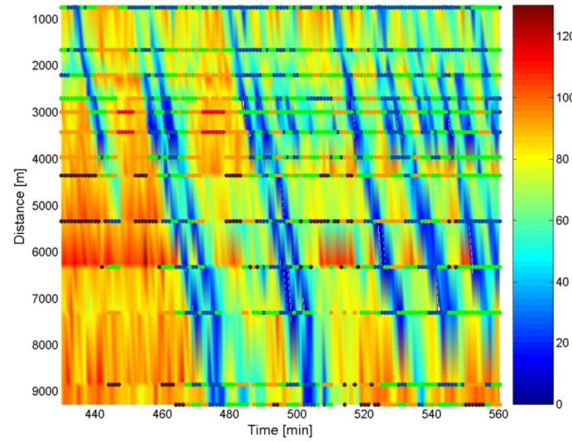

Figure 4: Daily morning congestion on the E313 and the displayed VSL (right lane; speed in km/h)

Since the VSL can differ between lanes, the assessment is based on vehicle trajectories per lane. In the remainder, if the VSL at a gantry is discussed, this refers to the VSL for a lane. The trajectories are calculated per lane from the detected speeds with an interval of 5 minutes. This interval is generally shorter than the frequency of the changing traffic conditions, so hereby a good representation of the DR and FAR as perceived by the drivers is obtained. Trajectories are composed for each continuous freeway section (being the two directions of the beltway and the direction of the E313 towards Antwerp). On- and off-ramps are hereby disregarded.

The situations to be detected are set to detected speeds on a trajectory below 70 km/h. This choice is based on the fact that 70 km/h is the highest VSL that can be directly requested by the control algorithm. Higher VSL are only displayed for gradually reducing speeds over multiple upstream gantries – or sometimes they are switched on manually. For the maximal allowable deviation, 20 km/h is chosen for both DR and FAR, since this is the interval between the VSL. Moreover, these parameters also correspond to the thresholds used in the control algorithms. Finally, it should be noted that a VSL of 50 km/h is never interpreted as a missed detection, since this is the lowest VSL.

Missed detections and false alarms are determined for all vehicle trajectories. The aggregate performance on the beltway and E313 are represented by the DR and FAR of Table 1.

Table 1: Aggregate performance of the VSL system

	DR (%)	FAR (%)
beltway	80.4	10.4
E313	60.5	7.6

Table 1 shows that the DR is reasonably high for the beltway, but considerably lower on the E313 due to the highly variable stop-and-go congestion pattern. Timely warning is here a difficult task. Moreover, quite a number of missed detections on the E313 are caused by the VSL being manually fixed to 70 and 90 km/h at some gantries on several occasions.

Furthermore, the FAR is very low (especially on the E313). Of course, on the one hand, this means that an alarm is a trustworthy message to drivers to adapt their speed and/or be more alert for downstream congestion. Thus, the system is reliable and credible in that respect. However, the DR and FAR seem imbalanced. Missed detections are much more frequent than false alarms, whereas avoiding the former should have priority since this implies direct safety benefits (the latter only indirect). The same imbalance can be noted (though less distinctly) on the beltway: missed detections are more frequent than false alarms. Directions for improvement of the system therefore lie in increasing the DR (especially in the stop-and-go patterns on E313). Thereby, also an increase of the FAR will be inevitable since the two are inversely correlated.

As explained in Section IV, local visualizations of the performance at some gantries or for specific periods of the day are a very helpful addition to the results in Table 1. Perspective is added to the global results and the local performance of separate gantries or periods of the day can be analyzed quickly. Weaknesses in the system can be easily pointed out and defining ways to improve the performance is facilitated. For instance, during the analyses, false alarms appeared to be concentrated at specific locations. It turned out that some detectors were malfunctioning, which was easily remedied by the road authority, herewith substantially improving the FAR of the system.

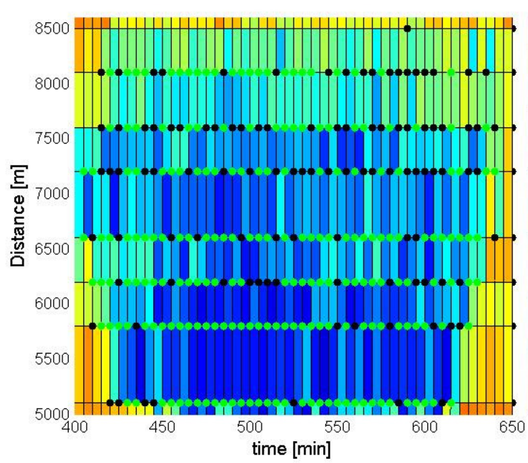

Figure 5: Visualization of successful (green) and missed (black) detections for daily congestion on the beltway (right lane; speed in km/h)

In Figure 5 and Figure 6, the DR is visualized in the congested areas on the beltway and the E313 (compare with Figure 3 and Figure 4). For each departure time of a vehicle trajectory (the horizontal axis), and for each section between two gantries (the vertical axis) the lower bound of the detected speed is plotted (see the color bar). In other words, a trajectory runs in the vertical direction, straight up from its departure time. Furthermore, the colored dots indicate the detections at each gantry, either successful (green) or missed (black). The FAR can be displayed analogously but is not shown here to not overload the paper.

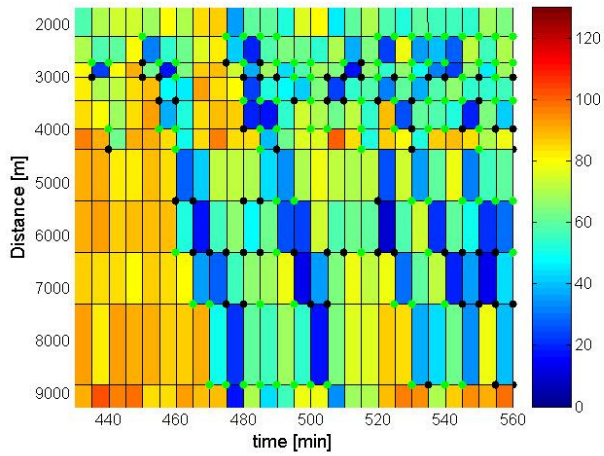

Figure 6: Visualization of successful (green) and missed (black) detections for daily morning congestion on the E313 (right lane; speed in km/h)

Firstly, in the congested area on the beltway (Figure 5) a lot of missed detections occur at the head of the queue (km 7,50–8,50). This is however not to be interpreted as a flaw of the system, since its function there is to encourage drivers to accelerate, in order to maximize the queue discharge rate. Therefore, fairly high VSL need to be displayed, which may on occasion lead to a missed detection. However, dangerously large speed differences are not to be expected here since the speed of the approaching vehicles is quite low. The statement that ‘the higher the DR, the better’, should therefore be somewhat put into perspective at this point.

Also further upstream in the congestion centre (km 6,00-7,50) a lot of missed detections occur. This is due to the fact that in that area the system allows an increase of the VSL from 50 to 70 km/h too easily (see also Figure 3). Because the accelerations in this area are generally short-lived, the VSL change frequently from 50 to 70 and back. On the one hand, this generates a decrease of safety (only slightly, since the speed differences are not too high). But also (and more importantly) these mild missed detections - which are in this case actually inappropriate encouragements to drivers to accelerate, rather than failing to warn for unexpected downstream congestion - and the volatility of the system - 43% of all VSL are sustained for less than a minute - have a negative influence on the credibility of the system.

A similar problem is apparent on the E313 (Figure 6). The VSL of 50 km/h are often lifted too early, before the congestion wave has fully passed a gantry, causing missed detections. In the next section, an adjustment to the VSL control is suggested that stabilizes the VSL during congestion to avoid mild missed detections and volatility. Since the speeds in the congested areas are generally too low to induce false alarms, it is safe to say that the credibility of the VSL system would benefit from this adjustment.

More important are missed detections at the queue tails (shockwaves between free flowing and congested traffic). Due to the large speed differences, these missed detections are more dangerous. Since the shockwave speed on the E313 is high (up to 20 km/h and more), timely warning is a difficult task. Even if the system could display an appropriate VSL on the upstream gantry immediately after a speed drop is detected, this reaction would come too late to warn drivers that have already passed this upstream gantry (and will meet the queue tail before the next gantry) at that time (see Figure 1). Therefore, an online short-term prediction of the congestion spillback wave (based on detector data and traffic flow theory) would be a very useful addition to the current VSL system. By predicting the trajectory of the shockwave, a warning could be displayed on an upstream gantry even before passage of the first vehicle that will meet the queue tail between this and the next gantry. Hereby it is acceptable to slightly overestimate the spillback speed since a false alarm due to early warning is less harmful than a missed detection. Adding a short-term prediction module to the VSL system is part of future research.

The analysis of this section indicates that the overall performance of the VSL system in Antwerp is quite good, with very few false alarms and a reasonably high DR. Therefore the system is likely to yield (considerable) safety benefits.

Despite the good performance overall, the analysis shows that the system would benefit from a (slight) increase of the FAR in favor of an increase of the DR; especially on the E313, where dangerous missed detections (involving large speed differences) are more frequent.

Depicting the local performance of the system (as in Figure 5 and Figure 6) allows finding out more precisely where and when missed detections can and should be avoided. Suggestions made here to improve the DR (and the volatility of the system) are:

- short-term predictions to avoid missed detections at queue tails
- stabilization of VSL during congestion, avoiding volatility and mild missed detections

The latter is discussed in the next section.

VI. VSL Stabilization during Congestion

In this section, a potential modification to the original VSL algorithm in Antwerp is analyzed using the DR and FAR definition and visualization of this paper. The proposed modification is a post processing on the original VSL that intends to keep the desirable properties in the acceleration and deceleration zones of the queue, while stabilizing the speeds posted in the congestion centre. By removing the volatile behavior in the congestion centre, the credibility and effectiveness of the system should be enhanced. If the congested traffic state is quite constant (in the congested zone), a constant VSL of 50 km/h (or maybe a 'traffic jam symbol') should be displayed (Figure 7). Only at the head of the queue (the acceleration zone), higher VSL are to be shown. This way, the increasing VSL are trustworthy messages to encourage drivers to accelerate efficiently from the queue, producing a high queue discharge rate.

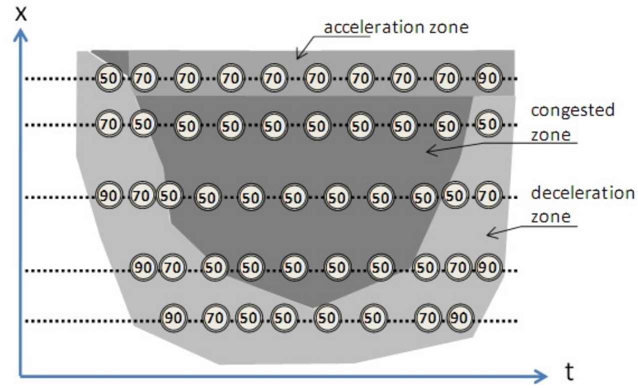

Figure 7: Intended functionality of the proposed VSL algorithm modification

Stabilization of VSL during congestion can be obtained in two ways: either by creating a bigger hysteresis in the algorithm (increasing the threshold for the transition of a VSL of 50 km/h to 70 km/h) or by fixing a VSL of 50 km/h for a certain time (as suggested in [14]). Since the performance of the first approach is more sensitive to poorly calibrated thresholds and errors in the data ([14]), the latter approach is chosen (being the more robust of the two). A post processing algorithm that extends the procedure in [14] is applied. The details of this algorithm are considered less relevant for this paper; rather it is shown how the DR and FAR definitions and visualization can be used to confirm the improved performance of the VSL system.

Since the proposed stabilization is not yet implemented on-field, the effect of the changes on the traffic states and drivers' speeds is neglected. Due to the poor compliance to the VSL that is apparent in the current data set, this approximation is justified. Furthermore, since the stabilization algorithm can only dictate VSL lower than the original ones, accounting for drivers' response to the changed VSL (i.e. lowering the detected speeds) would decrease the number of false alarms and leave the DR unaffected. Neglecting the drivers' response therefore (slightly) underestimates the performance of the stabilization.

The parameters in the post processing algorithm are calibrated in order to maximize the goal function $max(DR - FAR)$. This way, in the optimum any parameter change induces a marginal decrease of missed detections that is smaller than the marginal increase of false alarms. The FAR is chosen equally important here as the DR. Firstly, to not deviate too much from the original system, and secondly because the main benefit from the stabilization of VSL during congestion is an improved credibility of the system (i.e. the same benefit a low FAR has).

Based on the aforementioned parameter optimization and the assumption that the drivers' speeds do not change, a prediction of the overall performance of the modified VSL system is shown in Table 2. The DR has improved with 7.6 and 11.7% for the beltway and E313 respectively, at the cost of an increase of the FAR of only 1.8 and 2.3% respectively.

Table 2: Predicted performance of the adjusted VSL system

	DR (%)	FAR (%)
beltway	88.0	12.2
E313	72.2	9.9

The stabilization of VSL is also clear from comparison of Figure 8-Figure 9 with Figure 3-Figure 4.

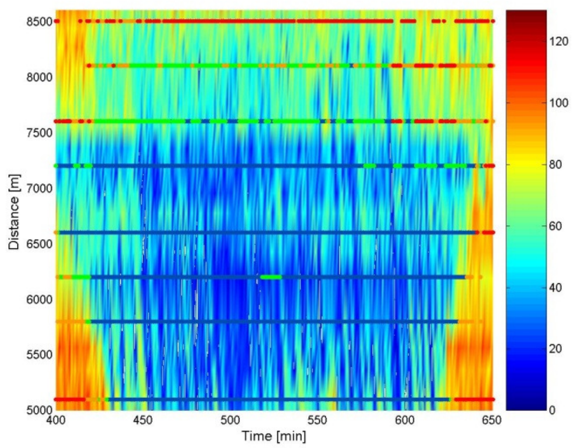

Figure 8: Daily congestion on the beltway and the stabilized VSL (right lane; speed in km/h)

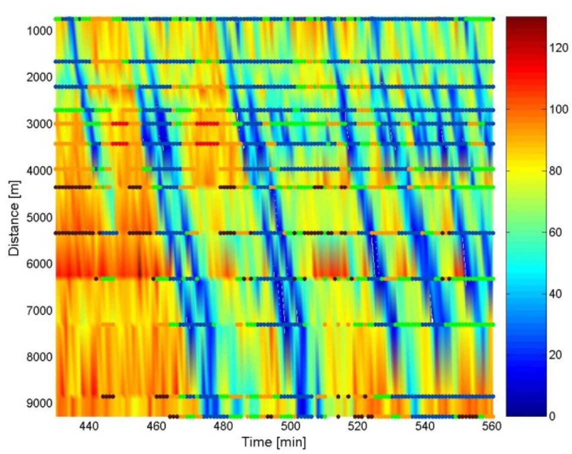

Figure 9: Daily morning congestion on the E313 and the stabilized VSL (right lane; speed in km/h)

Visualization of the DR for the beltway (Figure 10) clearly shows the improvement that was also apparent in the overall performance (Table 2). The improvement on the E313 is somewhat less obvious from Figure 11. This is due to the fact that quite some missed detections occur in between congestion waves (with detected speeds of 60-70 km/h). Improvement is mostly noticed in the wider congestion waves and in case of fast successions of waves (as in the upper right part of Figure 11). Note also that the VSL at the heads of the queue (where traffic needs to be encouraged to accelerate) are hardly affected and thus the queue discharge rate is not negatively influenced.

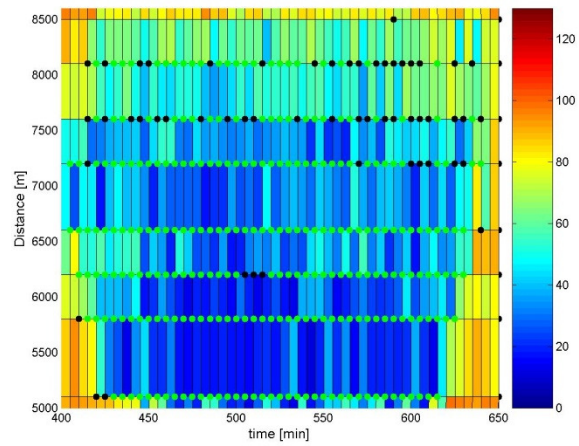

Figure 10: Visualization of successful (green) and missed (black) detections for daily congestion on the beltway after stabilization (right lane; speed in km/h)

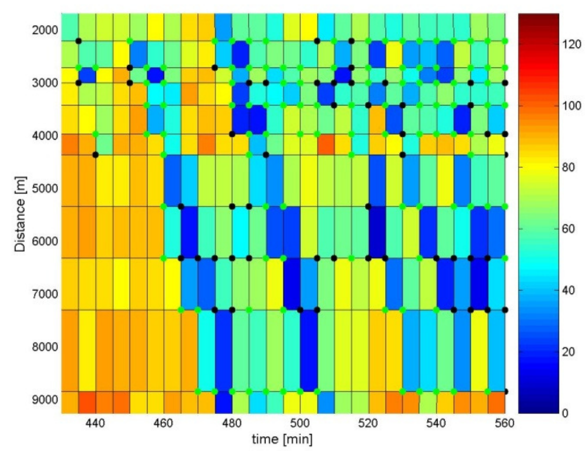

Figure 11: Visualization of successful (green) and missed (black) detections for daily morning congestion on the E313 (right lane; speed in km/h)

In conclusion, according to this ex-ante analysis, the presented method to stabilize VSL during congestion has the intended advantages. Firstly, it reduces the volatility of the system, thereby increasing the credibility. Secondly, the credibility benefits from the decrease of mild missed detections – from this, also safety benefits can be expected (be it limited). Thirdly, in the long run (as drivers become familiar with the system), this high credibility may lead to a slight increase of the queue discharge rate, as increasing VSL in the acceleration zone are trustworthy messages to drivers to accelerate from the head of a queue. Of course, the actual improvement can only be determined after implementation of the adjustment on-field. The same comparison of DR and FAR can then be made ex-post.

VII. CONCLUSION

The assessment method presented in this paper is based on the evaluation of DR and FAR defined from the drivers' perspective. This has the inherent advantage over existing definitions that it is in closer relation to the phenomenon it wishes to express, namely the effectiveness of warning drivers for downstream congestion or hazards. Furthermore, the DR and FAR are good indications of the credibility of a VSL system. Visualization of VSL, detections and alarms in direct comparison with the measured speeds allows easily pointing out weaknesses in the system and defining ways to improve the performance.

Using the presented method, the VSL system around Antwerp (Belgium) is evaluated. The primary conclusion is that the performance of the system is quite good, with a reasonably high DR and very low FAR. Furthermore, two suggestions for improvements are made:

- short-term predictions to avoid missed detections at queue tails
- stabilization of VSL during congestion, avoiding volatility and mild missed detections

The first improvement was beyond the scope of this project, but constitutes future research. Timely warning near shockwaves eliminates dangerous missed detections with large speed differences between approaching and downstream traffic and thus engenders considerable safety benefits.

For the stabilization, a modification to the original algorithm is suggested that would – based on an ex-ante analysis - increase the DR with 7.6 and 11.7% on the beltway and E313 respectively, at the cost of an increase of the FAR of only 1.8 and 2.3% respectively. In future research, the modified algorithm should be implemented on-field and the parameters further calibrated to maximize the performance of the system. Also stabilizing VSL of 70 km/h is an interesting experiment (especially on the E313). Stabilization outside of congested zones (VSL of 90 km/h or higher) seems less useful.

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